



INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification⁵ :

H04B 10/22

A1

(11) International Publication Number:

WO 91/0541

(43) International Publication Date:

18 April 1991 (18.04.91)

(21) International Application Number: PCT/US90/05766

(22) International Filing Date: 9 October 1990 (09.10.90)

(30) Priority data:

417,828

6 October 1989 (06.10.89)

US

(71) Applicant: MASSACHUSETTS INSTITUTE OF TECHNOLOGY [US/US]; 77 Massachusetts Avenue, Cambridge, MA 02139 (US).

(72) Inventors: SWANSON, Eric, A. ; Four Lincoln Street, Maynard, MA 01754 (US). BONDURANT, Roy, S. ; 343 Autumn Lane, Carlisle, MA 01741 (US).

(74) Agent: LEE, G., Roger; Fish & Richardson, One Financial Center, Suite 2500, Boston, MA 02111-2658 (US).

(81) Designated States: AT (European patent), BE (European patent), CA, CH (European patent), DE (European patent), DK (European patent), ES (European patent), FI (European patent), GB (European patent), GR (European patent), IT (European patent), JP, LU (European patent), NL (European patent), SE (European patent).

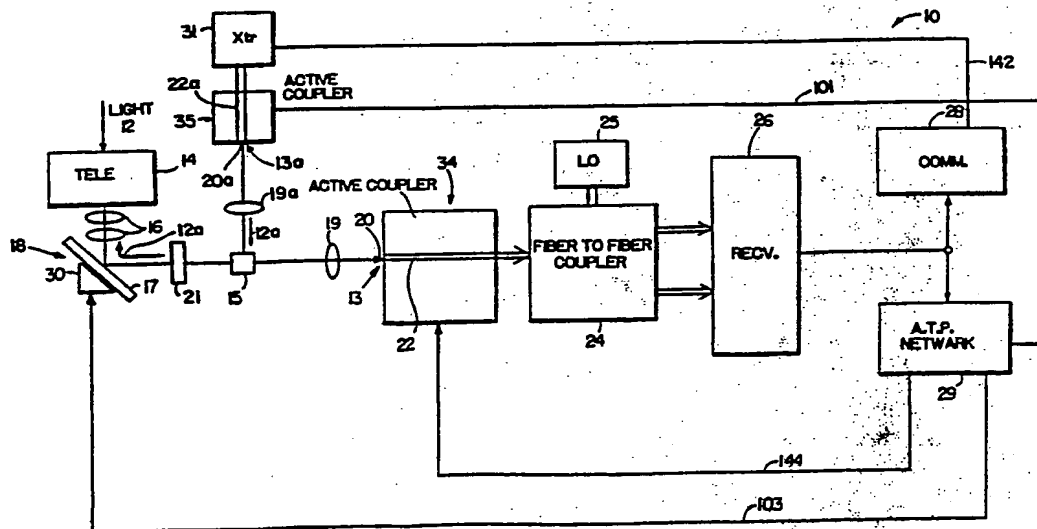
Published

*With international search report.**Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.*

(54) Title: FIBER-BASED FREE-SPACE OPTICAL SYSTEM

(57) Abstract

An optical system (10) has an optical package (28) operable with an acquisition, tracking and pointing network (29), the optical package (28) including a coupling device (34/35) and an optical fiber (22/22a) and acting to carry optical signals and to transfer them into/ou of the fiber (22/22a) the fiber (22/22a) transferring the signals from/to a transmitter/receiver (31/26). An aspect of the invention includes a coupling device (34) with a housing (36) to which is affixed a flexure (50). A fiber (22) extends along the flexure (50) and terminates about one end of flexure (50). An actuator (42, 44) is coupled between the flexure (50) and the housing (30). The flexure (50) is coupled to a detector (66, 68) to cooperate with the actuator (42, 44) for driving the flexure (50). The transmitter/receiver (31/26) cooperates with the acquisition, tracking and pointing network (29) to control the coupling device (34). Both coherent or non-coherent detection may be employed. Various features and embodiments are described.



FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AT	Austria	ES	Spain	MC	Monaco
AU	Australia	FI	Finland	MG	Madagascar
BB	Barbados	FR	France	ML	Mali
BE	Belgium	GA	Gabon	MR	Mauritania
BF	Burkina Faso	GB	United Kingdom	MW	Malawi
BG	Bulgaria	GR	Greece	NL	Netherlands
BJ	Benin	HU	Hungary	NO	Norway
BR	Brazil	IT	Italy	RO	Romania
CA	Canada	JP	Japan	SD	Sudan
CF	Central African Republic	KP	Democratic People's Republic of Korea	SE	Sweden
CG	Congo	KR	Republic of Korea	SN	Senegal
CH	Switzerland	LI	Liechtenstein	SU	Soviet Union
CM	Cameroon	LK	Sri Lanka	TD	Chad
DE	Germany, Federal Republic of	LU	Luxembourg	TC	Togo
DK	Denmark			US	United States of America

FIBER-BASED FREE-SPACE OPTICAL SYSTEMBackground of the Invention

The Government has rights in this invention pursuant to Grant Number AF19628-85-C-0002 awarded by the Air Force.

5 This application is a Continuation-In-Part of U.S.S.N. 07/299,088 filed January 23, 1989.

The present invention relates to fiber optics as applied to free-space coherent and incoherent optical systems.

10 The advantages of fiber optics in ground-based communication systems (whether telecommunications or radar, for example) is widely recognized. However, present space-borne optical systems (such as for communications and radar) typically rely on bulk optics, including mirrors and lenses rigidly mounted to an optical bench, to transfer light from
15 optical sources to the exit aperture or from the entrance aperture to the optical receiver. Such designs are typically sensitive to thermal and mechanical perturbations, and may substantially impact upon the host payload and real estate utilization.

20 Summary of the Invention

One aspect of the present invention includes a free-space optical system having an optical package having an interface with free-space and couplable to an acquisition, tracking and pointing network. The optical package includes
25 an optical fiber connection device for interacting with a communication device; the two devices cooperate to transfer optical signals therebetween. The package is configured to transfer the signals under guidance of the network at the interface with free-space.

30 Various embodiments of this aspect may include any of the following features: The communication device may be a receiver and the optical package may include at least one nutation device. The connection device may include an optical fiber, and the optical package may act to transfer the optical

-2-

signals into the fiber by nutation. The nutation device may include a beam steering mirror. The nutation device may include an active fiber coupler. The communication device may include a receiver and the optical package may further include

5 a beam steering mirror, an active fiber coupler, and an acquisition, tracking and pointing network. At least the mirror or the coupler may be nutated. The nutation device may be a mechanical nutation device having a housing to which is affixed a flexure, the fiber guided by the flexure and

10 terminating near an exposed end of the flexure, at least one actuator coupled between the flexure and the housing, or the nutation device may utilize an electro-optic or acousto-optic beam deflector in conjunction with a focusing lens to transfer signals into the fiber. The actuator may be electromagnetic,

15 piezo-electric or electrostatic. The nutation device may be driven at a mechanical resonance. The nutation device may further include at least one positional sensor coupled between the housing and the flexure. The nutation device may further include at least two positional sensors, output signals of

20 both sensors being applied to a position sensor amplifier section of the optical package, where the sensor output signals represent positional location of the fiber and which information is used to maximize coupling of the optical signals into the core of the fiber.

25 The communication device may be a receiver. The invention may further include a local oscillator and an optical fiber, the local oscillator providing a signal which is combined with the optical signal to perform coherent detection, and the fiber for coupling the receiver to the

30 optical fiber connection device preferably being single-mode, polarization-preserving. A GaAlAs diode laser may be used as a local oscillator laser having an output power of 30 mW and operable at a wavelength of 0.86 micrometers. The local oscillator and optical signals may be combined in a fiber

35 coupler. The combining coupler may be a 3 dB coupler. The

-3-

coupler may be coupled to a double balanced receiver. The position sensor output may be fed back to a dither generator to compensate for changes in the response of the nutation device. The system may include a beam steering mirror. The position sensor output may be applied to a demodulator to demodulate the receiver output signal, the demodulator output being applied via a loop compensation network to control position of the beam steering mirror.

The communication device may be a transmitter. The optical fiber connection device may include an optical fiber and the optical package may further include at least one active fiber coupler. The active fiber coupler facilitates the transfer of the optical signal from the optical fiber connection device to a target external to the system. The active fiber coupler may utilize nutation techniques. The active fiber coupler may be a mechanical device including a housing with a flexure affixed to the housing.

The fiber may be guided by the flexure, terminating near an exposed end of the flexure. At least one actuator may be coupled between the flexure and the housing. The actuator may be electromagnetic, piezo-electric, electrostatic, electrooptic or acoustooptic. The active fiber coupler may further include at least one positional sensor coupled between the housing and the flexure or two positional sensors, output signals of both sensors being applied to a position sensor amplifier section of the optical package, such that the sensor output signals are used to control the angular direction of the optical signal the fiber. The positional sensor output may be used to direct the optical fiber to be used in bore-sighting the optical system. The positional sensor output may be used to direct the optical fiber to transmit a signal which is pointed ahead of a remote receiver location. The position sensor output may be fed back to a dither generator to compensate for changes in the response of the nutation device. The optical package may include an acquisition, tracking and

BEST AVAILABLE COPY

pointing network.

In another aspect of the invention, where a focusing element focuses a received light beam at a desired focal point, a fiber-based receiver unit for free-space optical communication includes a tracking network and an active fiber coupler. A structure for translating an optical fiber is defined by the active fiber coupler such that the optical fiber has a terminus locatable approximately near the focal point. The active fiber coupler is disposed to radially control the translating structure to translate the optical fiber terminus about the focal point, the fiber intended to be coupled to a receiver, the active fiber coupler couplable via the receiver to the tracking network, the tracking network including actuation circuitry for assuring that the terminus of the optical fiber is maintained at or very near the focal point.

Various embodiments of this aspect may include any of the following features: The received light beam may be directed to the focal point via a beam steering mirror. The active fiber coupler may be a nutation device and may include at least one nutation position sensor. The tracking network may include a loop compensation network for actively controlling the position of the mirror responsive to nutation position signals supplied by the position sensor. The nutation device nutation may be actively compensated by a position control network responsive to the nutation position signals. The position control network may include a position sensor amplifier and a dither generator. The receiver unit may further include a local oscillator, the output of which is combined with the received light beam in a fiber optic coupler, the output of the latter being coupled to the receiver. The receiver may be double balanced. The fiber optic coupler may be a 3dB coupler. The fiber and coupler may be polarization preserving. The output of the receiver and of the position sensor may be coupled to a demodulator,

the receiver so coupled via a bandpass filter and a detector for detecting the nutation signal imposed upon the received light beam.

In another aspect of the invention, an optical system for at least transmitting or receiving unguided optical signals includes an optical package, the optical package including at least a transmitter optical fiber connection device or a receiver optical fiber connection device, and at least a transmitter module or receiver module couplable to an acquisition, tracking, and pointing network. The transmitter module transfers signals to the optical package by means of the transmitter optical fiber connection device. The optical package is configured to transfer the signals over an unguided channel to a target external to the optical system. The receiver module receives optical signals from the optical package by means of the receiver optical fiber connection device. The optical package is configured to receive optical signals from the target via the unguided channel.

Various embodiments of this aspect may include any of the following features: The receiver optical fiber connection device may include an optical fiber, and coupling of the optical signals from the optical package into the receiver optical fiber may be facilitated by nutation. The nutation may be accomplished by radial electromagnetic, piezoelectric, or electrostatic mechanical displacement of a tip of the optical fiber, the tip being located in a focal plane of a focusing element. The nutation may also be accomplished by electro-optic, acousto-optic, or electro-mechanical angular deflection of a received optical beam as a focusing element focuses the light into the receiver optical fiber. The transmitter optical fiber connection device may include an optical fiber, and coupling of the optical signals from the transmitter optical fiber to the external target may be facilitated by nutation. Angular direction of the transmitted optical signals from the optical package may be

controlled by radial electromagnetic, piezoelectric, or electrostatic mechanical displacement of a tip of the transmitter optical fiber, the tip being located in a focal plane of a collimating lens. Angular direction of the transmitted optical signals from the optical package may be controlled by electro-optic, acousto-optic, or electro-mechanical angular deflection of the transmitted optical signals after a collimating lens has collimated the light from the optical fiber.

10 In another aspect of the invention, a nutation device includes a housing to which a flexure is affixed. A fiber extends along the flexure and terminates about one end of the flexure. An actuator is coupled between the flexure and the housing. The flexure is coupled to a detector to
15 cooperate with the actuator for driving the flexure at its mechanical resonance. The nutation device may include at least one position sensor and a dither generator, whereby changes in the device may be actively corrected so that the nutator will be nutated at a desired dither frequency and
20 amplitude.

A fiber-based transmission unit includes a lens element for transferring a light beam at a desired focal point, with an active fiber coupler and an optical fiber connection device (such as an optical fiber) coupled to the
25 active fiber coupler, the optical fiber connection device having a terminus approximately near the focal point, the active fiber coupler disposed to radially translate the optical fiber connection device terminus about the focal point, and the network including actuation circuitry for
30 assuring that the connection device terminus is maintained at or very near the focal point.

Other advantages and features will become apparent from the following description of the preferred embodiment and from the claims.

Description of the Preferred Embodiment

First we briefly describe the drawings.

FIG. 1 is a block diagram of a fiber-based coherent optical system in practice of the present invention.

5 FIG. 2a is a side view of one embodiment of an active fiber coupler.

FIG. 2b is a cross-sectional view of the coupler of FIG. 2a taken along line A-A in FIG. 2a.

10 FIG. 3 is a block diagram of a preferred fiber-based coherent optical system in practice of the present invention.

FIG. 4 is a block diagram of a preferred transmitter in practice of the present invention.

15 FIG. 5 is a graphical representation of closed-loop and rejection transfer functions in practice of one embodiment of the present invention.

In a free-space optical system, optical fibers can enable remotely locating the transmitter laser, local oscillator laser (in the case of coherent systems), and the receiver, spaced apart from the front-end optics. This yields flexibility in the mechanical, thermal, and electrical design which can enable reduction of size, weight and stability requirements of the optical module and can lead to easier integration and better utilization of the host platform.

25 Key elements of a fiber optic optical module are the receiver and transmitter subsections. The receiver preferably not only will perform the communication or radar signature function, but will also serve as a spatial tracking sensor to the line-of-sight deviations induced by the host platform.

30 FIG. 1 shows a block diagram of a fiber-based coherent optical system 10 in practice of the present invention which can perform both the communication function and tracking function. (Note that for non-coherent systems the same block diagram applies with the exception of the local oscillator 25 laser and optical coupler 24.)

35

The information-carrying light beam (or field) 12 is collected and transmitted using a telescope and course pointing device, such as a gimballed optical telescope 14, so as to apply light beam 12, via mirror 17 of steering mirror assembly 18, to an optical fiber 22. More particularly, when receiving, telescope 14 images light beam 12 via relay optics 16 onto the surface of steering mirror 17, which in turn directs light beam 12 through $\lambda/4$ wave plate 21 and diplexer 15 and then via a focusing lens 19 to a focal point 13 (which point is desired to coincide with the exposed end of core 20 of optical fiber 22).

Alternatively, when transmitting, lens 19a collimates light beam 12a from focal point 13a (which point is desired to coincide with the exposed end of core 20a of optical fiber 22a) through diplexer 15 and $\lambda/4$ wave plate 21 onto the surface of steering mirror 17. Steering mirror 17 directs light beam 12a via relay optics 16 out telescope 14.

It is preferable that the free-space coupling end of optical fibers 22 and 22a be carried in active fiber couplers 34 and 35. Active fiber coupler 34 functions as a receiver signal coupler and active fiber coupler 35 functions as a transmitter signal coupler. It is possible that such devices could incorporate piezo electric or electrostatic technology. However, an electro-magnetic actuator is preferred.

For a coherent system, as shown in FIG. 1, when system 10 functions as a receiver, light beam 12 is combined with light from a local oscillator laser 25 by means of a fiber optic coupler 24, the combined signals are then passed via a receiver (such as a dual balanced receiver) 26 as an electronic signal to a communications package 28 (which conventionally processes the communication data supplied by signal light beam 12) and also to an acquisition, tracking and pointing network 29. Preferably, network 29 is electrically coupled to both the active fiber coupler 34 (via

line 144), and to an actuator assembly 30 (via line 103) which drives beam steering mirror 17. In such embodiment, the acquisition, tracking and pointing network 29 acquires or angularly tracks the received signal beam 12 by driving mirror 17 and coupler 34 so as to position light beam 12 upon core 20 of optical fiber 22 at focal point 13 to maximize coupling of the light beam from free-space into the fiber.

When system 10 functions as a transmitter, remotely located transmitter 31 provides a signal light beam via optical fiber 22a to fiber optic coupler 35. Transmitter 31 is controlled by (or is responsive to) an electronic signal received (via line 142) from communications package 28. Acquisition, tracking and pointing network 29 is connected (via line 101) to active fiber coupler 35 to angularly point the transmitter beam signal (light beam 12a) by radially displacing the core end 13a of fiber 22a to maximize coupling of the light beam from the fiber to a target. Again, network 29 also may be engaged to control the position of mirror 17, as described above.

As seen in FIGS. 2a, 2b, a preferred active fiber coupler 34 includes a housing 36 to which are coupled magnetic poles 38, 40. These poles are provided with actuator coils 42, 44, respectively. Active fiber coupler 34 may thus function as a nutator. (It will be understood, however, that the present invention contemplates that nutation can be provided in many forms, such as via moving coils and fixed magnets or moving magnets and fixed coils, using piezoelectric, electrostatic or electrooptic devices, for example.) Optical fiber 22 is mounted within a flexure element 50 and preferably terminates at a first end 52 of flexure 50 (which is the location at which light beam 12 is applied from free-space to fiber core 20). (For coherent systems, the fiber and fiber optical coupler each are preferably single mode and polarization preserving. For non-coherent systems, no such coupler is required and the fiber

-10-

need not be polarization preserving.)

Coupler 34 thus may form a part of a tracking error sensor by employing standard nutation techniques. A dither generator imposes a small circular scan on coupler 34 by
5 actuation of flexure 50. (A larger dither amplitude increases tracking performance but decreases communication performance.) Tracking error signals are extracted by synchronously detecting the amplitude of the nutation signal. The resulting error signals are fed back to correct for tracking errors.

10 Flexure 50 is flexibly coupled to housing 36 by means of flexing joint 51 (although we have recently fabricated flexure 50 as a spring element without a joint 51, with good results). Whether with or without joint 51, flexure 50 is preferably configured to develop a desired mechanical
15 response (amplitude and phase) at the desired nutation frequency. For example, the nutator will nutate at a frequency of approximately 10 times the desired beam steering mirror bandwidth. In order to use small, low power mechanical actuators, the mechanical resonance of the flexure can be
20 designed to provide a mechanical amplification at the desired nutation frequency. This mechanical resonance feature is optional, although favorably incorporated into the preferred embodiment described herein.

FIG. 2a shows nutation device 34 having two opposed
25 positional sensors 66, 68. These sensors are optional, although they are favorably incorporated in the preferred embodiment described herein.

Active fiber coupler 35 is structurally similar to active fiber coupler 34. However, while active fiber coupler
30 34 desirably has a small dynamic range and a high bandwidth, active fiber coupler 35 desirably has a large dynamic range and a low bandwidth to provide high positioning accuracy. The dynamic range and bandwidth of couplers 34, 35 may be controlled by adjusting the stiffness of flexure 50. For
35 example, the stiffer that flexure 50 is made, the lower the

-11-

low frequency amplitude and the higher the resonant frequency which is obtained. For the transmitter coupler, the flexure is made weak to provide high amplitude low frequency deflection, which are necessary to perform boresight and point-ahead functions. A bandwidth of ~100 Hz is probably more than sufficient to keep pace with the rate of change in the required point-ahead angle. The dynamic range is dictated by that needed for boresight plus that needed for point-ahead.

10 Turning now to FIG. 3, a preferred embodiment of a fiber-based free-space optical system 10 includes telescope 14 and relay optics 16 as well as communication package 81 and acquisition and tracking controller 82. When system 10 is functioning as a receiver, relay optics 16 apply light beam 15 12 to mirror 17 of beam steering mirror 18, which in turn directs light 12 through $\lambda/4$ waveplate 21 and diplexer 15. When receiving, $\lambda/4$ waveplate 21 converts circular polarization to linear polarization, which is then directed via a polarization diplexer 15 toward the receiver portion of 20 the system. Focusing lens 19 then focuses the light beam at focal point 13 near the end of core 20 of optical fiber 22. The optical fiber is presented to the light beam by means of fiber coupler 34 which may function as a nutation device.

When system 10 is functioning as a transmitter, the 25 light beam which is provided near focal point 13a by core 20a of optical fiber 22a is collimated via lens 19a to provide a linearly polarized signal to diplexer 15. Diplexer 15 provides the linearly polarized signal (orthogonal to the received signal) to $\lambda/4$ waveplate 21 which in turn provides 30 a circularly polarized light beam (in the opposite sense of the received light) to mirror 18, which in turn directs the light beam through relay optics 16 and out telescope 14. The light beam is presented to focal point 13a by means of fiber coupler 35.

35 In the preferred embodiment, for a coherent system,

BEST AVAILABLE COPY

when receiving a signal, a single-mode, polarization-preserving fiber 22 preferably is used to carry light beam 12 to a single-mode polarization-preserving coupler 70. The other input to coupler 70 (preferably a 3 dB coupler) contains
5 light from a local oscillator laser 72, which is provided via a single-mode, polarization-preserving fiber optic cable 23. For non-coherent systems, the coupler and local oscillator are not required and the fiber need not be polarization preserving. Optionally, a Faraday isolator 74 (and
10 collimating and focusing lenses 73, 75) may be used to minimize feedback to the local oscillator laser, since isolation is critical to system performance. Laser 72 may be, for example, a GaAlAs diode laser, having an output power of 30 mW, operated at a wavelength of 0.86 micrometers.

15 The local oscillator field and the applied light field are combined in coupler 70. The combined signal is carried by means of fiber outputs 76, 78 to a receiver (preferably a double balanced receiver) 80. This receiver, in turn, is electrically coupled to a communications package
20 81 and acquisition and tracking controller 82.

The output signal 84 of receiver 80 is applied to demodulator 90 of controller 82 through a noise limiting bandpass filter 86 and detector 88. The electrical signal output from detector 88 contains information relating to the
25 dither signal imposed (via nutation device 34) onto the received optical power in fiber 22 and is applied to demodulator 90. Also, position sensor amplifier 92 couples information from nutation position sensors 66, 68 to demodulator 90.

30 Nutation driver circuit 100 includes a dither generator 102 and a power amplifier 104, which, in a simplified embodiment of the present invention, can apply a constant amplitude signal (such as a sine wave) to the nutation driver circuit (magnets 38, 40 and respective coils
35 42, 44). A constant sinusoidal signal causes the nutator to

-13-

oscillate in a circular manner at a desired frequency (such as 10 kHz), without any direct error compensation. In the preferred embodiment, the nutation driver circuit 100 is configured to compensate for any drift in the characteristics of coupler 34 to ensure that fiber core 20 oscillates in a circular manner at the desired frequency (which in the case of the resonant fiber nutator is at or near the mechanical resonance). Preferably, information from position sensor amplifier 92 is applied to dither generator 102. Dither generator 102 in turn responsively corrects for drift by varying its output in order to drive fiber core 20 in coupler 34 in a circular scan at the desired nutation frequency as best as possible centered at focal point 13, while at the same time the position sensor amplifier 92 output applied to demodulator 90 will apply tracking errors via loop compensator 94 and power amp 96 to actuator 30 of beam steering mirror assembly 18 to reposition mirror 17, so as to apply light beam 12 as best as possible dead-center to core 20 at focal point 13.

In one embodiment, demodulator 90 continually correlates the output from detector 88 with the position of fiber core 20. If the output of detector 88 is unchanged over one or more nutation cycles, then no repositioning signal need be applied to the steering mirror actuator 30 to reposition mirror 17. However, if the output of detector 88 is changing over one or more nutation cycles, then the demodulated tracking error signal is applied to drive actuator 30 by means of loop compensation and power amplifier circuits 94, 96. That is, demodulator 90 can favorably correlate the position of fiber core 20 with received power to extract tracking information, so as to provide error compensation to steering mirror assembly 18 to better position focal point 13 at the exposed end of core 20. (While FIG. 3 is one dimensional, it will be appreciated that the tracking and correlation process is responsive in both azimuth and elevation.)

BEST AVAILABLE COPY

-14-

When the system is functioning as a transmitter, communication electronics 81 instructs (via line 102) transmitter 31 to provide a signal via polarization-preserving single-mode optical fiber 22a to active fiber coupler 35. The location of core 20a is controlled by controller 110 in response to a pointing command input 141 derived from boresight, target, and/or ephemeris information, generated in any conventional manner. More specifically, sensors 66a and 68a of fiber coupler 35 provide information to transmitter position sensor 92a. Transmitter signal generator 112 uses this information in conjunction with the command input 141 to determine whether core 20a is correctly positioned and, if not, provides a control signal to power amp 114 to correct the core position.

System 10 can, without the use of any external signals, automatically perform a boresight function. The boresight function is required in order to compensate for misalignments due to launch loads and on-orbit thermal and mechanical disturbances. Boresight may be accomplished, for example, by flipping a retro-reflector 107 into the transmitted beam after $\lambda/4$ waveplate 21 or by directing mirror 17 to a retro-reflector 106 located external to the optical system. The reflected transmitter light from the retro-reflector (now polarized in the opposite sense) is directed onto receiver fiber coupler 34. Using standard detection techniques, the transmitter fiber coupler 35 can be displaced until the power into receiver coupler 34 is maximized, thus accomplishing boresight. The transmitter and receiver fiber couplers 34, 35 may be mounted in close proximity to one another to minimize the range required for boresight. In a preferred embodiment, due to the close proximity of transmitter and receiver fiber couplers 35, 34 and the short optical path between the couplers, a dynamic range of approximately ± 5 beamwidths (or core diameters) is sufficient to accomplish the boresight function.

-15-

The required point-ahead angle is approximately equal to the differential tangential velocity between system 10 and the location to which system 10 is transmitting divided by the speed of light. A point-ahead angle of $\sim 52\mu\text{rad}$ is sufficient for most applications. For example, an antenna having a beamwidth of $4\mu\text{rad}$ results in a dynamic range requirement of ± 13 beamwidths. Therefore the total required dynamic range is ± 18 beamwidths. For example, at $0.86\mu\text{m}$ wavelength, ± 1 beamwidths corresponds to approximately $\pm 82\mu\text{m}$ of fiber core translation.

In order to ensure that the point-ahead angle is accurately implemented, high precision position sensors 66a, 68a are preferred on transmitter fiber coupler 35. High DC stability insures that the boresight position is accurately maintained. High precision and repeatability also insures that the proper point-ahead displacement from boresight is achieved.

While actuation of the steering mirror assembly can be eliminated by feeding back position signals directly to the active fiber coupler 34 only, there are two reasons for including such actuation. First, its use can increase dynamic range. Second, the point-ahead requirement for free-space communication systems is more easily implemented by combining the transmit and receive beams (with the appropriate angular offset) after the steering mirror has tracked out platform disturbances. In order to support the tracking loop bandwidths necessary for free-space optical communication systems (such as open-loop cross-over frequencies of 100 Hz to 1 kHz) dithering at high frequency (such as at approximately 1 kHz to 10 kHz) is preferred.

Referring to FIG. 4, transmitter 31 is shown in detail with a pair of lasers 120, 122. However, any number of lasers (including a single laser) may be used. Lasers 120, 122 provide laser beams that are collimated and circularized using anamorphic prism pairs, sent through an optical isolator

BEST AVAILABLE COPY

-16-

and focused via focusing lens systems 124, 126, respectively, to maximize the coupling into the polarization preserving optical fibers 128, 130. The optical fibers are then provided to fiber interface device 132 (e.g., since there are two
5 lasers, a 2:1 fiber switch or other active and passive fiber components) which manipulates the incoming optical signals (e.g., multiplexes the signals or combines the signals). The manipulated signal is then provided to fiber coupler 35. Alternately, redundancy may be provided by nesting the cores
10 of two (or more) fibers close together within fiber coupler 35.

Transmitter 31 requires high coupling efficiency, low feedback, and redundancy. An unfortunate consequence of maintaining high coupling efficiency is the associated high
15 sensitivity to feedback. In order to minimize the effects of feedback into transmitter lasers 120, 122, over 60 dB of isolation is desired. In a preferred embodiment, Fresnel reflections from the input and exit fiber facets can effectively be minimized by polishing the fiber facets on an
20 angle and anti-reflection coating.

FIG. 5 shows the measured closed-loop and rejection transfer functions that were obtained in one embodiment by feeding back the error signal output of demodulator 90 to a typical, two-dimensional fast steering mirror assembly 18.
25 (These measurements apply for both azimuth and elevation axes.) This design included a 9 kHz dither frequency, 500 Hz open-loop cross-over frequency, and 43° of open-loop phase margin. The resulting -3 dB closed-loop bandwidth is approximately 1.1 kHz.

30 It will now therefore be understood that the present invention makes it possible to accurately position the focal point 13 (or 13a) of the received field 12 (or 12a) at the exposed end of the fiber core 20 (or 20a) of fiber 22, (or 22a) so as to optimally transfer light beam 12 (or 12a) from
35 free-space into the fiber (or vice versa). This is achieved

-17-

by means of, in one embodiment, steering the light beam by actuation of the beam steering mirror assembly 18 and generating an error signal (such as by dithering the beam steering mirror or by means of separate optical detectors, e.g., quadrant detectors). In another embodiment, improved coupling may be achieved by use of an active fiber coupler (such as a dithered nutation device) 34 (or 35), which can be responsively driven to assure accurate coupling of beam 12 (or 12a) into fiber 22 (or 22a) at focal point 13 (or 13a). In a preferred embodiment, nutation device 34 (or 35) and steering mirror assembly 18 are both responsively controlled to assure accurate coupling of beam 12 (or 12a) into fiber 22 (or 22a) at focal point 13 (or 13a), using a dithering technique for generation of error signals.

Other embodiments are within the following claims.
What is claimed is:

BEST AVAILABLE COPY

-18-

CLAIMS

1 1. A satellite optical system comprising
2 an optical package having an interface with free space and
3 couplable to an acquisition, tracking and pointing network,
4 the optical package including an optical fiber connection
5 device for interacting with a transmitter, the fiber
6 connection device cooperating with the transmitter to transfer
7 optical signals therebetween, the package configured for
8 transferring the signals under guidance of the network at the
9 interface with free-space.

1
2 2. The system of claim 29 wherein the optical
3 fiber connection device includes an optical fiber and the
4 optical package further comprises at least one active fiber
5 coupler, the active fiber coupler facilitating the transfer
6 of the optical signal from the optical fiber connection device
7 to a target external to the system.

1 3. The system of claim 30 wherein the active fiber
2 coupler utilizes nutation techniques.

-19-

1 4. The system of claim 30 wherein the active fiber
2 coupler is a mechanical or electromagnetic device.

1 5. The system of claim 30 wherein
2 the active fiber coupler is a mechanical device
3 including
4 a housing,
5 a flexure affixed to said housing, the fiber
6 guided by the flexure and terminating near an exposed end of
7 the flexure, and
8 at least one actuator coupled between said
9 flexure and said housing.

1 6. The system of claim 33 wherein said actuator
2 is electromagnetic, piezo-electric, or electrostatic.

1 7. The system of claim 30 wherein the active fiber
2 coupler utilizes an electro-optic or acousto-optic beam
3 deflector to control the angular direction of the optical
4 signals from the fiber.

1 8. The system of claim 33 wherein the active fiber
2 coupler further includes at least one positional sensor
3 coupled between said housing and said flexure.

1 9. The system of claim 33 wherein said active fiber
2 coupler further includes at least two positional sensors, said
3 sensors providing output signals representing a positional
4 location of the fiber, and said output signals being used to
5 control the angular direction of the optical signals from the
6 fiber.

1 10. The system of claim 37 wherein the positional
2 sensor output is used to direct the optical fiber during bore-
3 sighting the optical system with a receiving optical system.

BEST AVAILABLE COPY

-20-

1 11. The system of claim 37 wherein the positional
2 senor output directs said optical fiber to transmit a signal
3 which is pointed ahead of a remote receiver location.

1 12. The system of claim 37 wherein the positional
2 sensor output directs said optical fiber during scanning of
3 the optical system.

1 13. The system of claim 29 wherein the optical
2 package includes the acquisition, tracking, and pointing
3 network.

1 14. An optical system for at least transmitting or
2 receiving unguided optical signals comprising
3 an optical package,
4 the optical package including at least a transmitter
5 optical fiber connection device or a receiver optical fiber
6 connection device, and
7 at least a transmitter module or receiver module
8 couplable to an acquisition, tracking, and pointing network,
9 the transmitter module transferring signals to the
10 optical package by means of said transmitter optical fiber
11 connection device, the optical package configured to transfer
12 said signals over an unguided channel to a target external to
13 the optical system,
14 the receiver module receiving optical signals from
15 the optical package by means of said receiver optical fiber
16 connection device, the optical package configured to receive
17 optical signals from the target via the unguided channel.

1 15. The system of claim 42 wherein the receiver
2 optical fiber connection device includes an optical fiber and
3 coupling of the optical signals from the optical package into
4 the receiver optical fiber is facilitated by nutation.

1 16. The system of claim 43 wherein the nutation is
2 accomplished by radial electromagnetic, piezoelectric, or
3 electrostatic mechanical displacement of a tip of the optical
4 fiber, said tip being located in a focal plane of a focusing
5 element.

1 17. The system of claim 43 wherein the nutation is
2 accomplished by electro-optic, acousto-optic, or
3 electromagnetic angular deflection of a received optical beam
4 as a focusing element focuses the light into said receiver
5 optical fiber.

1 18. The system of claim 42 wherein the transmitter
2 optical fiber connection device includes an optical fiber and
3 coupling of the optical signals from the transmitter optical
4 fiber to the external target is facilitated by nutation.

1 19. The system of claim 46 wherein angular direction
2 of the transmitted optical signals from the optical package
3 is controlled by radial electromagnetic, piezoelectric, or
4 electrostatic mechanical displacement of a tip of said
5 transmitter optical fiber, said tip being located in a focal
6 plane of a collimating lens.

1 20. The system of claim 46 wherein angular direction
2 of the transmitted optical signals from the optical package
3 is controlled by electro-optic, acousto-optic, or
4 electromagnetic angular deflection of the transmitted optical
5 signals after a collimating lens has collimated the light from
6 said optical fiber.

-22-

1 21. A fiber-based transmission unit operable with
2 a lens element for transferring a light beam at a desired
3 focal point, comprising
4 a communication device whose transmissions are
5 controllable by a control network,
6 an active fiber coupler and an optical fiber
7 connection device coupled to the active fiber coupler, the
8 optical fiber connection device having a terminus
9 approximately near the focal point, the active fiber coupler
10 disposed to radially translate the connection device terminus
11 about the focal point, and the network including actuation
12 circuitry for assuring that the connection device terminus is
13 maintained at or very near the focal point.

1 / 4

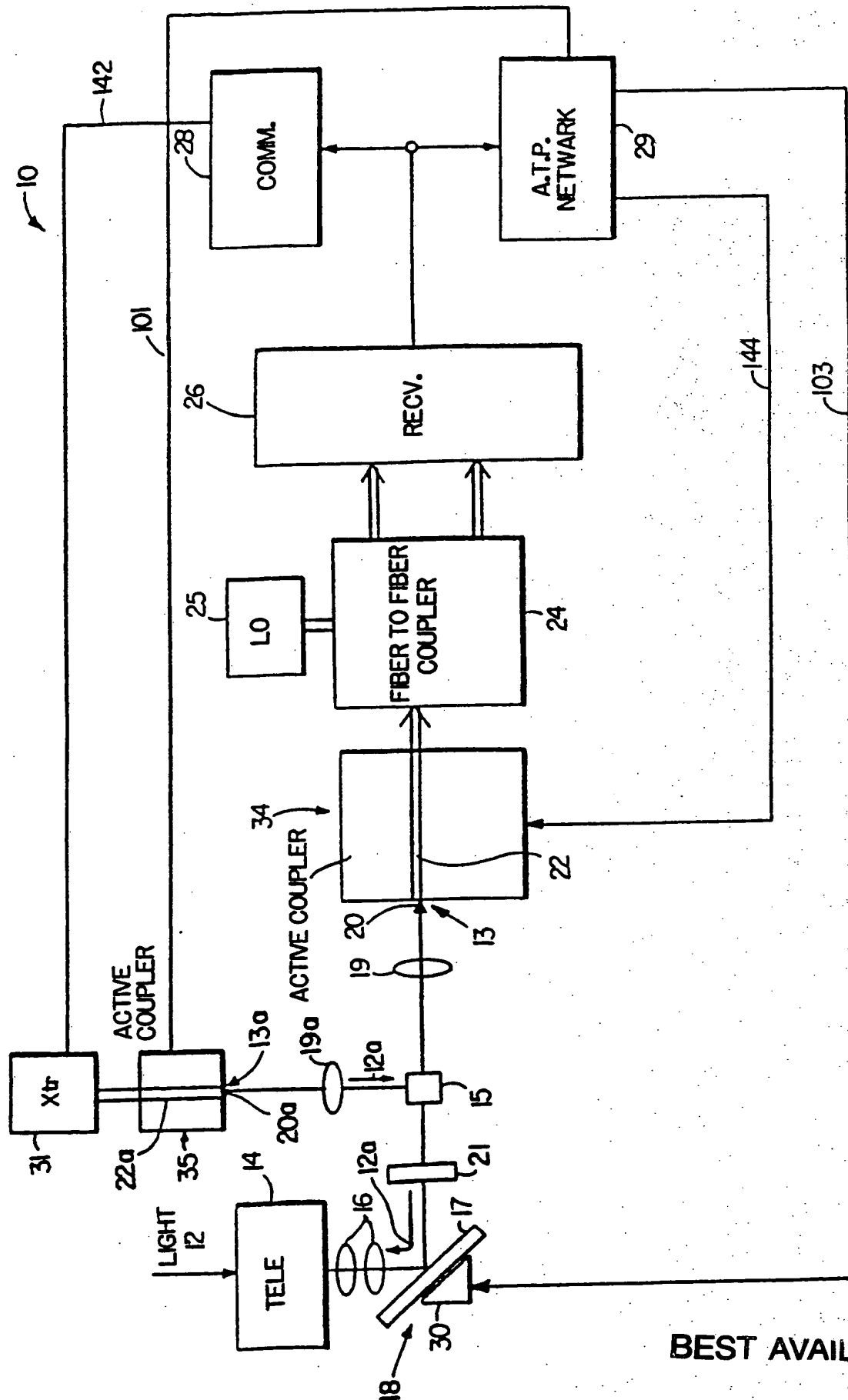
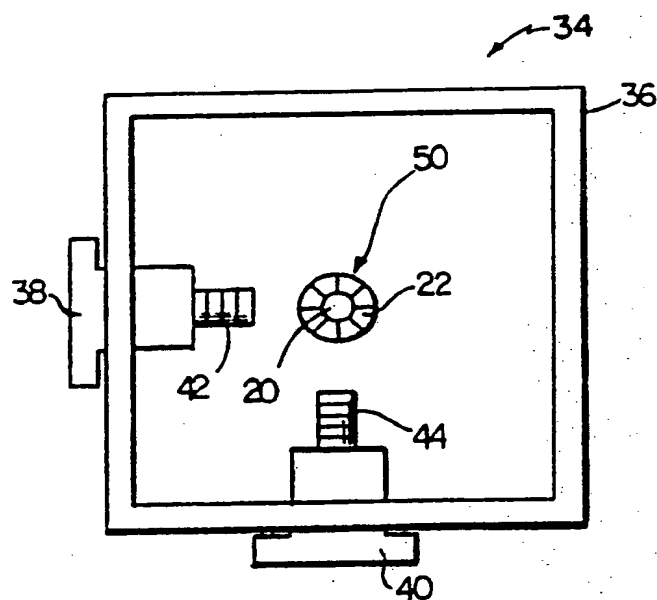
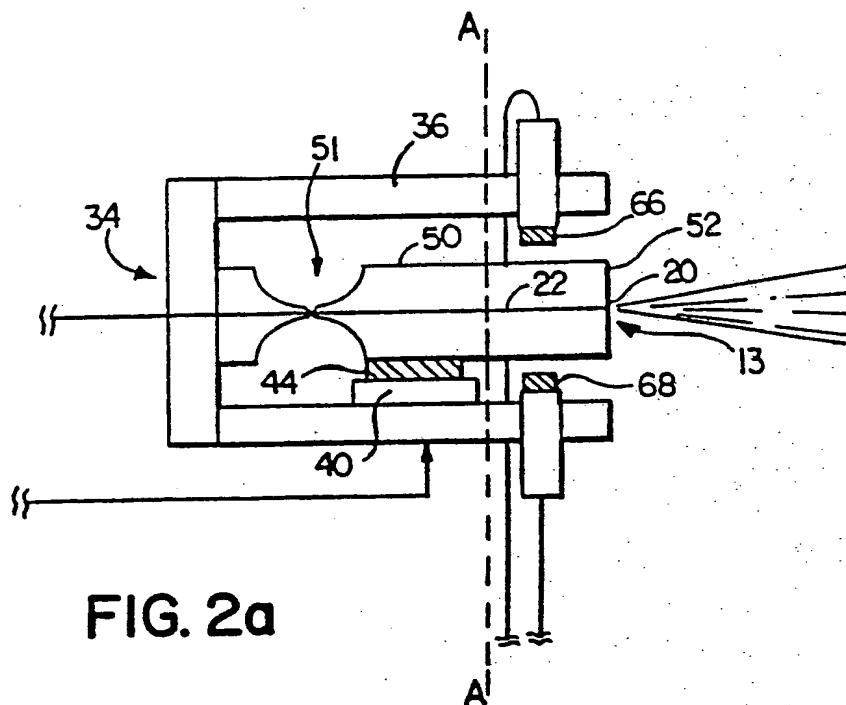


FIG. 1

BEST AVAILABLE COPY



4 / 4

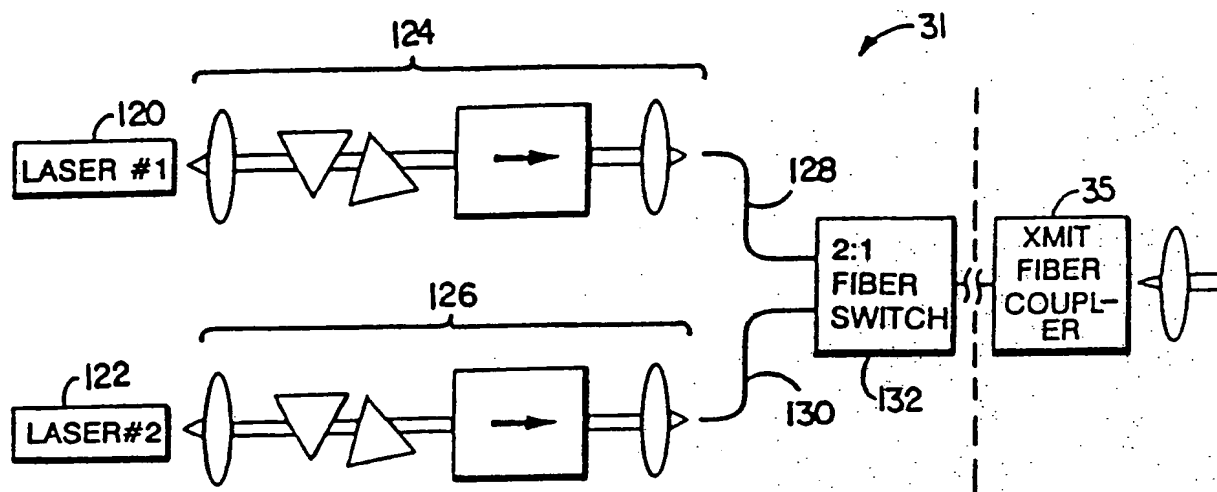


FIG. 4

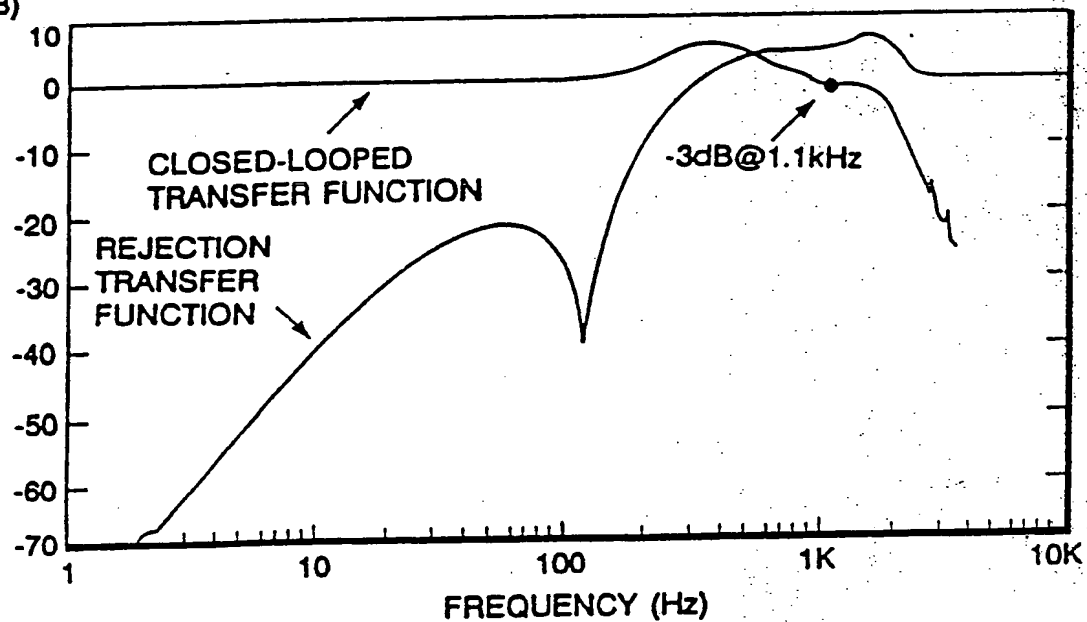
FREQUENCY
RESPONSE
(dB)

FIG. 5

FURTHER INFORMATION CONTINUED FROM THE SECOND SHEET

V. ☐ OBSERVATIONS WHERE CERTAIN CLAIMS WERE FOUND UNSEARCHABLE¹

This international search report has not been established in respect of certain claims under Article 17(2) (a) for the following reasons:

1. ☐ Claim numbers _____, because they relate to subject matter not required to be searched by this Authority, namely:

2. ☒ Claim numbers 2-13 and 15-20, because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out¹, specifically:
the claims are dependent upon non-existent claims.

3. ☐ Claim numbers _____, because they are dependent claims not drafted in accordance with the second and third sentences of PCT Rule 6.4(a).

VI. ☐ OBSERVATIONS WHERE UNITY OF INVENTION IS LACKING²

This International Searching Authority found multiple inventions in this international application as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims of the international application.

2. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims of the international application for which fees were paid, specifically claims:

3. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claim numbers:

4. ☐ As all searchable claims could be searched without effort justifying an additional fee, the International Searching Authority did not invite payment of any additional fee.

Remark on Protest

☐ The additional search fees were accompanied by applicant's protest.

☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

International Application No **PCT/US90/05766**

I. CLASSIFICATION OF SUBJECT MATTER (If several classification symbols apply, indicate all) ³		
According to International Patent Classification (IPC) or to both National Classification and IPC IPC (5) : HO4B 10/22 U.S. CL. 607		
II. FIELDS SEARCHED		
Minimum Documentation Searched ⁴		
Classification System	Classification Symbols	
<div style="display: flex; justify-content: space-between;"> 455/619, 606, 607, 617; 350/484, 487; </div> <div style="display: flex; justify-content: space-between;"> U.S. 250/203 R; 356/152. </div>		
Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched ⁴		
III. DOCUMENTS CONSIDERED TO BE RELEVANT ¹⁴		
Category ⁶	Citation of Document, ¹⁶ with indication, where appropriate, of the relevant passages ¹⁷	Relevant to Claim No. ¹⁵
Y	Proceeding of the Society of Photo-optical instrumentation engineers, vol. 103 21 April 1977. "Shipboard electro-optic system intergration," Giannavis, Robert J., and Mooradian, Gregory C.	1, 14, 21
Y	Johnson, " High Precision Muhi postion singlemode fiber swncn using magnetic levitation, "SPIE Vol. 734 fiber optics 87: Fifth International Conference on fiber optics and opto-Electronics, 1987.	1, 14, 21
<div style="display: flex; justify-content: space-between;"> <div style="width: 45%;"> <p>⁸ Special categories of cited documents: ¹⁸</p> <p>"A" document defining the general state of the art which is not considered to be of particular relevance</p> <p>"E" earlier document but published on or after the international filing date</p> <p>"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)</p> <p>"O" document referring to an oral disclosure, use, exhibition or other means</p> <p>"P" document published prior to the international filing date but later than the priority date claimed</p> </div> <div style="width: 45%;"> <p>"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention</p> <p>"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step</p> <p>"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.</p> <p>"&" document member of the same patent family</p> </div> </div>		
IV. CERTIFICATION		
Date of the Actual Completion of the International Search ¹		Date of Mailing of this International Search Report ¹
14 JANUARY 1991		07 FEB 1991
International Searching Authority ¹		Signature of Authorized Officer ¹⁹
ISA/US		<i>Nguyen Ngoc Ho</i> NGUYEN NGOC HO GEOFF SUICLIFE INTERNATIONAL DIVISION